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of Engineers

Techniques for Measuring and Analyzing Inlet Ebb-Shoal Evolution

by Donald K. Stauble

PURPOSE: The Coastal Engineering Technical Note herein provides techniques to measure and analyze the evolution of ebb shoals associated with tidal inlets.

PROBLEM: Tidal inlets are one of the most dynamic features along a coastline. The complex temporal and spatial interactions of waves, tides, and longshore currents create and constantly modify the morphology and sedimentary structures found at tidal inlets. Quantification of the magnitudes, rates, and patterns of geomorphic change is central to sediment budget calculations, estimation of dredging requirements, and assessment of whether inlet changes have had a significant effect on adjacent beaches. Inlet shoals are also potential sources of sand for beach fill and sand bypass projects. Mining of these shoals can provide a local source of needed sand. These engineering activities will modify natural coastal processes and change the inlet sediment pathways and channel morphology. Engineering objectives at inlets (providing a stable navigation channel and locating low-cost sand-borrow sources) need to be met without adversely impacting the inlet or adjacent shorelines. Before new construction or modification of existing engineering begins, the historic evolution of the inlet and how engineering alternatives might modify the existing inlet morphodynamics should be understood.

OBJECTIVE: Typically, tidal inlets have large sand bodies that form as tidal shoals in the ocean and bay adjacent to the inlet opening. The ebb-tidal shoal is the sand accumulation seaward of the inlet throat. This sediment feature is formed primarily by ebb-tidal currents depositing sediment in the ocean. The ebb current has strong velocities in the inlet's throat, but the current slows as it opens into the larger water body. Waves and longshore currents then modify the shape of the shoal. Various morphologic models have been identified depending on whether the tidal forces or wave forces are the dominant processes and how they vary through time (i.e., Oertel 1975; Hayes 1980; Boothroyd 1985; Gibeaut and Davis 1993; FitzGerald 1996). This technical note focuses on techniques to evaluate the evolution of the inlet ebb shoal and to understand historic patterns of erosion and accretion. These techniques can be adapted to study the flood-tidal shoal (the sand accumulation formed in the bay or lagoon, landward of the inlet throat) and channel shoals (which are sand bodies that form in the throat, the section of the inlet between the adjacent shores). These sand deposits are found adjacent to or in a channel, where reduced tidal flow and wave activity promote the deposition of sand. This channel shoaling may require dredging to maintain the navigation channel.

TYPES OF DATA REQUIRED AND DATUMS: To evaluate and measure how an inlet and its ebb shoal have evolved over time, in both a natural configuration and after engineering structures have been constructed, specific data sets are required. With the increasing access to Geographic Information System (GIS) software, analysis of shoal evolution has been made

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This Coastal Engineering Technical Note (CETN) provides techniques to measure and analyze the evolution of ebb shoals associated with tidal inlets.

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easier. GIS technology can take historic data sets of various scales, datums, and types and georeference them all to a common scale, datum, and format. A range of horizontal datums exists in historic data such as the North American Datum of 1927 (NAD27) and more recently 1983 (NAD83). Most Districts use the state plane coordinate system, but latitude/longitude and Universal Transverse Mercator grid are also common. A single datum should be identified and all surveys converted to the chosen common standard. Likewise, many vertical datums have been used in the historic records, such as National Geodetic Vertical Datum of 1929 (NGVD29) and more recently the North American Vertical Datum of 1988 (NAVD88); a common vertical datum needs to be chosen for consistency in analysis. Typical types of data useful in ebb-shoal analysis process are listed below.

Shoreline Positions: These positions are compiled from District survey sheets, National Oceanic and Atmospheric Administration (NOAA) topographic sheets (called T-Sheets), United States Geological Survey (USGS) topographic maps, aerial photography, and in some States, compiled historic shoreline archives available from the responsible State agency. These data are necessary to evaluate the effect response of the adjacent shore to the ebb shoal as it evolves over time. The techniques described require a baseline defined by the shoreline.

Care must be taken to identify which shoreline is being represented in the data sets. In most studies, historic shoreline positions are determined from various sources, such as nautical and topographic charts, aerial photography and beach-profile surveys. The historic shorelines on NOAA T-sheets are identified as the "mean high-water" line, but this is rarely true. Several references (Shlowitz 1962, 1964; Anders and Byrnes 1991; Crowell, Letherman, and Buckley 1991; and Kraus and Rosati 1997) explain that the early NOAA field surveyors usually mapped a geomorphic feature (the upper berm crest or high-water debris line) to determine the shoreline for standard mapping and charting purposes. Shorelines identified from aerial photography can be the dune or cliff line, high-water debris (Stafford 1971), or sometimes the wet/dry line identified by visible color or gray-tone shading change. On some bathymetric maps, the mean low-water or mean lower low-water line is also used to depict a shoreline . The mean high-water line can also be measured from surveyed beach profiles (Kraus and Rosati 1997). Thus, T-sheet shorelines, shorelines derived from aerial photographs, or chart-depicted shorelines are not necessarily the mean high-water shoreline and if mistaken as such may create errors in shoreline change calculations. All shoreline position data must be converted to the same defined line type to reduce error in identification of shoreline position and interpretation of shoreline evolution.

Bathymetric Surveys: These surveys are compiled from District bathymetric survey sheets, NOAA hydrographic sheets (called H-Sheets, some of which are available in digital form from NOAA's National Geophysical Data Center and via their website), and surveys performed for Inlet Navigation Districts or State agencies.

Bathymetric data need to be in a digital format for analysis in any GIS. If the data are not in digital format from the original source, they may be digitized from the paper copy. If possible, original Mylar sheets should be obtained, because they are the most stable and will produce the most accurate digitized record. A common vertical datum must also be established. The most common historic Corps datum is usually mean low water, but NOAA has recently switched to

mean lower low water. Horizontal datums and map projections must also be accounted for when digitizing and converting to a common system.

Aerial Photography: Aerial photography is compiled from District archives, various Federal agencies such as the U.S. Department of Agriculture-Natural Resources Conservation Service, NOAA-Coast and Geodetic Survey, NOAA-National Ocean Service, USGS, and National Aeronautics and Space Administration, and some State and local agencies.

If aerial photography is taken at or near low tide, the high-water line or wet/dry line can be identified and mapped as a useful shoreline. However, its significance relative to other shorelines established by surveying techniques or from charts may be difficult to determine, and its variability over time may be great because of seasonal beach cycles, the impact of storms, and temporal tide and water table variability. Portions of ebb and flood shoals are often visible either directly or identifiable from wave breaking or refraction patterns. Although photographs do not show the entire area of the shoals, they show relative positions. This information can be used to complement bathymetric data and identify relative changes in shoal areal extent and in channel migration. Aerial photographs can be scanned and the resulting digital file imported into some GIS packages, where the photographs can be georeferenced and displayed as background files. However, control points may not always be available on the photography, limiting accurate georeferencing. The area and patterns of shoals, shoreline positions, and channel orientations can then be measured from the photography and incorporated within the GIS analysis.

EBB-SHOAL EVOLUTION ANALYSIS: The first task is to identify adequate historic coverage of the entire ebb shoal. Often historic coverage of the ebb shoal is limited to only the navigation channel. This section will examine the techniques used to study the development of an ebb-tidal shoal using a study of Ocean City Inlet, Maryland, as an example (Stauble and Cialone 1996). Ocean City Inlet proved to be a good case study because it was formed as a breach caused by a hurricane in 1933, and historic data existed for the pre-inlet coast. A search of available Ocean City Inlet data produced 10 historic bathymetric data sets collected from various sources that covered the entire ebb shoal. This excellent record documents the development of the ebb shoal from its initial formation and serves as an example of how techniques described herein have been applied to measure and analyze ebb-shoal growth patterns.

Identification of Ebb-Shoal Boundary: Before any calculations of ebb-shoal properties can be done, the boundary of the ebb shoal has to be chosen. Standardized techniques to identify these boundaries do not exist. Once a bathymetry map has been constructed for a particular survey time period, the landward, seaward, and updrift and downdrift boundaries can be chosen. Most nearshore areas typically have straight and parallel contours. Ebb shoals usually disrupt this pattern and deflect the contours around the shoal. The seaward extent of the shoal may therefore be defined where the contours return to a more parallel configuration to the coast. The updrift and downdrift sides of some shoals can be identified by the sharp angle the contours make with the prevailing coastal bathymetry. Other shoal edges may be more difficult to identify if the shoal shape is symmetric and has gradual changes in contour position relative

to surrounding contours. The landward boundary identification is possibly the most variable between inlets and presents the greatest challenge to determine. Portions of the ebb shoal episodically migrate shoreward at unjettied inlets. Small sections of the ebb shoal may become isolated on the landward side of non-shore-normal navigation channels. The navigation channel may isolate a section of the ebb shoal. Engineering structures such as jetties will modify the channel, which may affect the landward boundary of the ebb shoal. For all of these reasons, judgment will be required to identify where the shoal ends and the shoreface, throat channel, and structure influence begin.

Bathymetric Analysis: Beginning with the earliest reliable data, one can construct a digital file by producing a Digital Terrain Model (computer-generated, three-dimensional model of a surface) consisting of the horizontal (x,y) and vertical (z) components of the digital bathymetric data. The software connects adjacent points to form an array of triangles. This Triangular Integrated Network (TIN) represents the surface. From the TIN, a contour map is created by specifying a contour interval that will show sufficient details. The bathymetry may then be merged with the closest available shoreline position data and the process repeated for each successive bathymetric and shoreline data set.

Calculations can be made using the historic bathymetry data sets to quantify the evolution of the ebb shoal's offshore extent and alongshore width. Choice of a contour to represent the shape of the ebb shoal will vary, depending on the morphology of each specific ebb shoal. The 7-m-depth contour was selected in the Ocean City study because it gave a good measure of the extent of the ebb shoal. A distance measured from the tip of the south jetty parallel to the throat to the 7-m contour characterized the offshore extent of the shoal at the time of each survey. Ebb-shoal width was portrayed as the distance along the line perpendicular to the line measuring offshore extent that connects the 7-m-depth contour at its widest separation north and south of the inlet. This ebb-shoal width line was located around 700 m seaward of the south jetty at Ocean City. From this analysis, a pattern of shoal growth in the offshore and asymmetrical growth to the south in the alongshore direction was measured (Figure 1).

Volume and Area Calculations: One of the first methods to calculate ebb-shoal volumes was given by Dean and Walton (1975). Hicks and Hume (1997) recently applied Digital Terrain Modeling to calculate shoal volume, performed with SURFER software. Three methods are presented in this CETN to calculate the change in volume of the ebb shoal and the areal extent of the shoal over time. Each of these methods has merits, depending on the type and extent of data available. In this present work, ebb-shoal area and volume were calculated using INTERGRAPH MGE Terrain Analysis software. Other software packages are commercially available from comparing digital terrain change over time.

Ebb-Shoal Edge Method - This method calculates a volume contained beneath the bathymetric surface and above a fixed horizontal plane. The 13-m-depth contour was identified as the base of the ebb shoal deposit beyond which the computed profile cross sections through the shoal indicated little change (Figure 2). Volume calculations were then computed between consecutive time periods for the data sets from 1933, 1937, 1962, 1978, and 1995. Analysis of data sets from 1981, 1983, 1986, 1988, and 1990 could not be included because of the limited

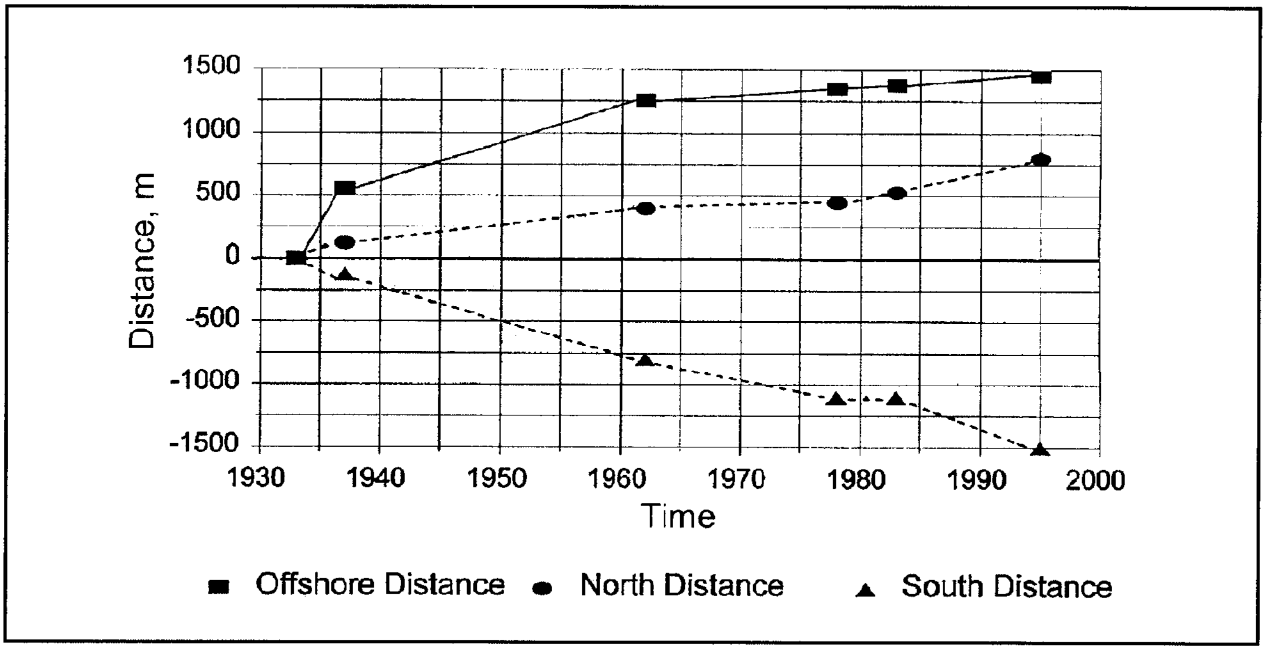

Figure 1. Historic growth of seaward and alongshore components of ebb shoal

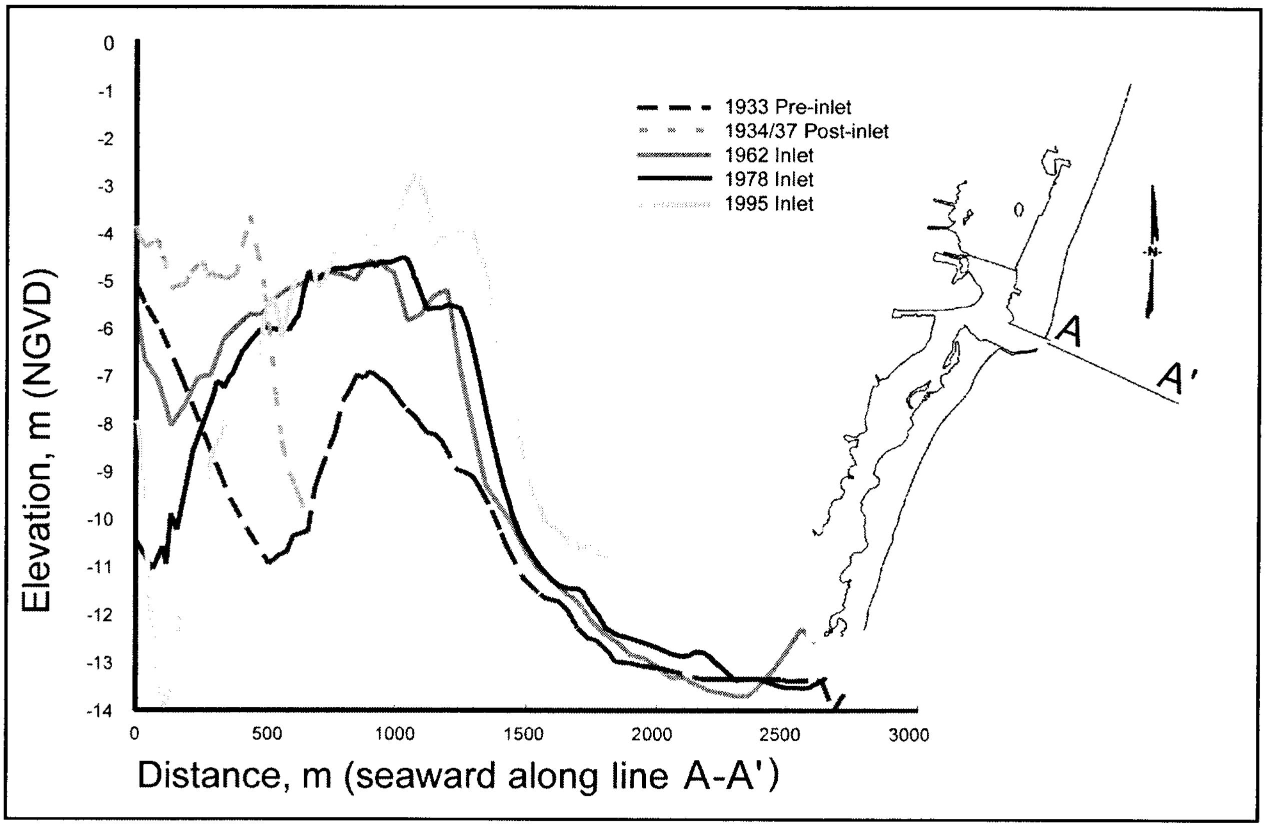

Figure 2. Profiles along center line of inlet showing seaward and vertical ebb-shoal growth at Ocean City

area covered by those surveys. This is a common problem where surveys are confined to the navigation channel and do not include bathymetric data of the entire extent of the ebb shoal.

The volume was computed for each Ocean City data set within a boundary polygon. Figure 3 illustrates three boundary areas used in calculating ebb-shoal volume. Three boundary areas were needed because of the high rate of retreat in the southern shoreline position and the growth in shoal area during the study. The 1933 and 1962 volumes were calculated within the intermediate-size box. This box used the 1933 Assateague shoreline as the southern land boundary, since the shoreline was the boundary in 1933 and the 1962 shoal was detached from any shoreline. A smaller box was used for the 1937 shoal volume because of the minimal extent of shoal growth and area of survey coverage limited to just the new ebb shoal. A third large box was used for the rest of the volumes that had the 1995 south shoreline as a landward boundary. This expanded box was needed to cover the full extent of the shoal as the shoreline retreated and the shoal attached to the shore in this area.

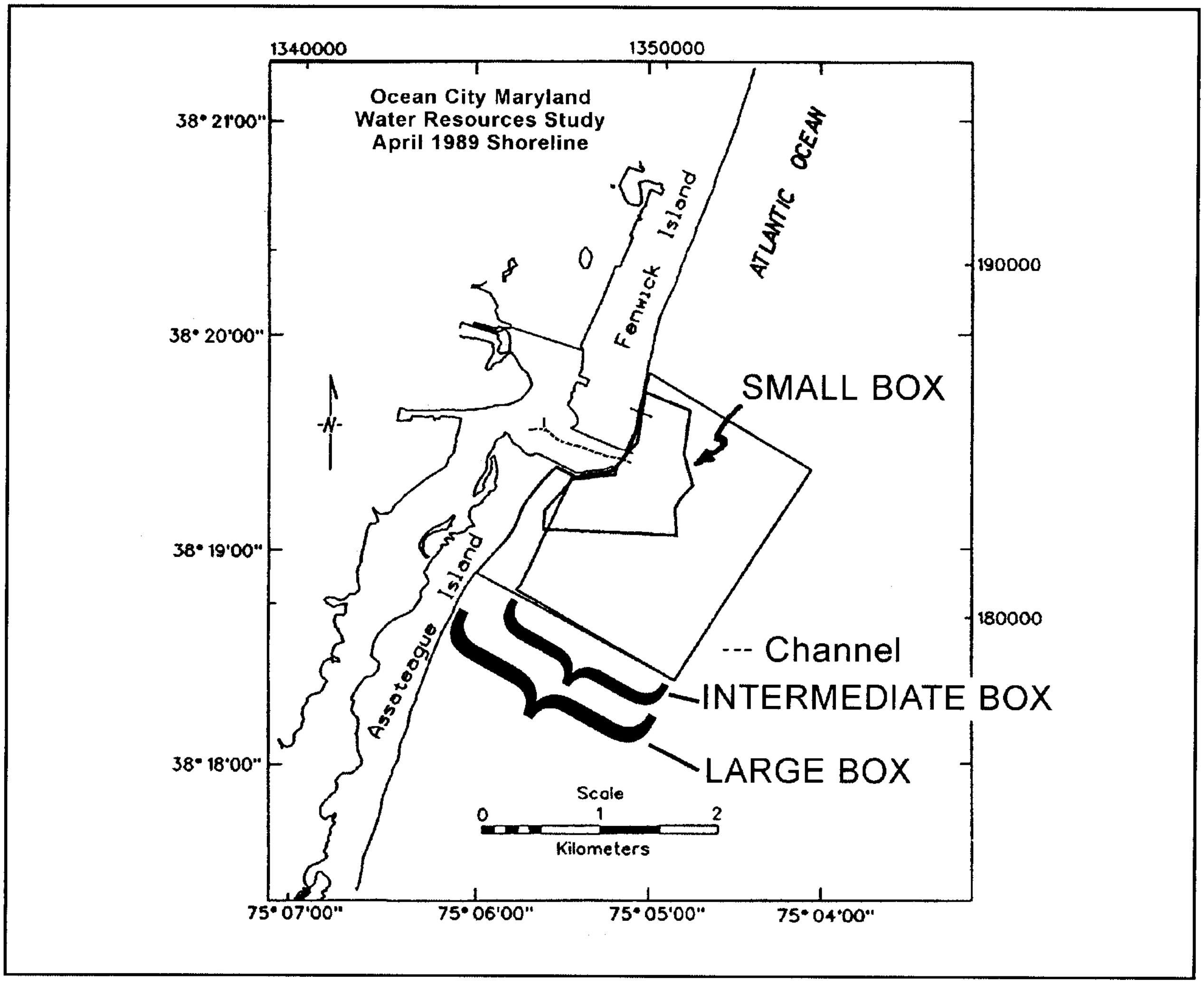

Figure 3. Boundary area used in ebb-shoal volume calculations

Table 1 lists area and volume change values between each consecutive survey period to illustrate how calculated changes from bathymetric data can quantify inlet-shoal-evolution trends. Figure 4 plots the volume growth of the ebb shoal from 1933 (pre-inlet) to 1995 out to the 13-m-depth contour. After the rapid formation rate of 3.17×10^5 m^3/year of the new ebb shoal from 1933 to 1937, a slower growth rate of 1.23×10^5 m^3/year occurred from 1937 to 1962. Between 1962 and 1978, the rate increased to 2.90×10^5 m^3/year, and from 1978 to 1995, it decreased to 7.90×10^4. As of 1995, the total volume of the shoal was around 10.0×10^6 m^3 of sediment. Over the 62 years of the study, the average growth rate was 166,500 m^3/year.

Table 1
Ebb-Shoal Volume and Area Changes Calculated by Three Methods at Ocean City Inlet, Maryland

	13-m Contour		Difference Maps		Residual	
Date	Volume Change $\times 10^6$ m^3	Area $\times 10^6$ m^2	Volume Change $\times 10^6$ m^3	Area $\times 10^6$ m^2	Volume Change $\times 10^6$ m^3	Area $\times 10^6$ m^2
Jun 1933	0	0	0	0	0	0
Mar 1937	1.27	0.82	1.35	0.73	-	-
May 1962	4.34	3.34	5.85	2.57	5.30	1.83
Aug 1977 Oct 1978	8.98	3.67	8.25	2.26	7.95	2.51
Nov 1981	Survey less than coverage					
May 1983	Survey less than coverage					
Jan 1986	Survey less than coverage				9.21	2.34
Oct 1988	Survey less than coverage					
Jun 1990	Survey less than coverage					
Jul, Oct, Dec 1995	10.32	3.64	10.84	2.21	9.87	3.05

Note: All volume and area values are cumulative from 1933.

Difference Map Method - Another approach for calculating volume and area change for the ebb shoal utilizes difference maps. The bathymetric surface from one time period was subtracted from the surface for the next time period creating an elevation difference map between consecutive surveys. Volumes were calculated from each elevation difference map, within the appropriate boundary polygons explained above. Ebb-shoal expansion was defined as the increase in planform area above 0 m but within the boundary polygon. The volume and area were calculated above the 0-m contour of elevation change, which represented the accretion of the shoal. These individual difference volumes were added cumulatively using the data sets that covered the full extent of the study area (1937, 1962, 1978, and 1995) and were very close to the 13-m-depth contour values (Table 1). Using this method, rate of shoal growth was 174,800 m^3/year over the 62 years of the study versus 166,500 m^3/year using the previous method.

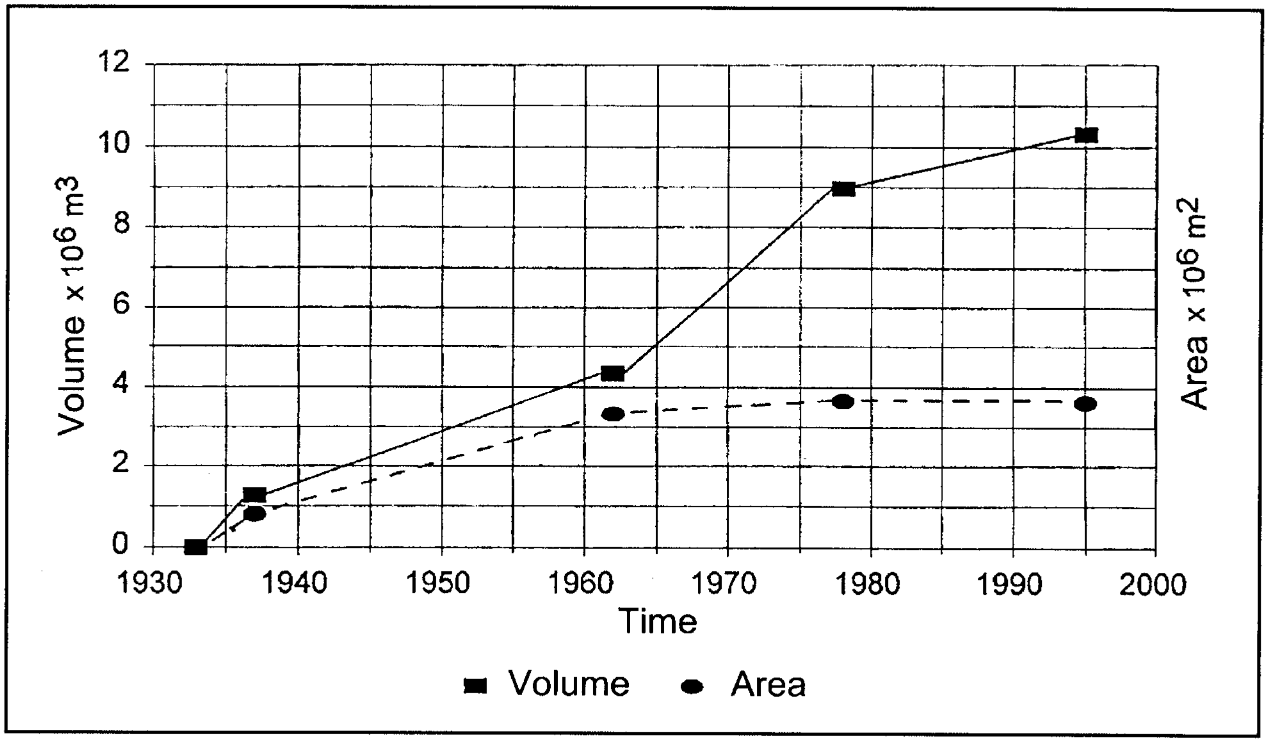

Figure 4. Ebb-shoal volume growth from 1933 to 1995 out to 13-m contour at Ocean City Inlet

Residual Method - Dean and Walton (1975), Walton and Adams (1976), and Marino (1986) describe a methodology for calculating volume in ebb shoals by reference to idealized no-inlet contour lines. Hicks and Hume (1996) developed a residual method for analyzing ebb-delta shapes and volumes. The residual method fits a digital terrain to a no-delta pre-inlet bathymetry (actual 1933 pre-inlet bathymetry in this case) and to each of the other bathymetries (1962, 1978, 1986, and 1995), and a "residual shoal surface" is calculated by subtracting these bathymetries from the base no-delta condition. Volumes were calculated from greater than the 0-m contour from this residual surface. The polygon was the large area in Figure 3. In the residual method, a no-inlet bathymetry needs to be defined. In areas where inlets have existed through recorded time, Hicks and Hume (1996) suggest creation of an idealized no-inlet bathymetry using a typical equilibrium shape profile from areas of shore and seafloor outside the shoal area and replacing the existing ebb-shoal bathymetry. In this study of Ocean City Inlet, the pre-inlet 1933 data set was adequate for representing the pre-ebb shoal area. A problem arose in defining a pre-inlet bathymetry at the northern end of Assateague Island, which has eroded one island width over the study period. The 1933 shoreline was replaced with the present more landward 1995 shoreline, and a typical present-day bathymetry outside the influence of the inlet was substituted in the area between the 1933 and 1995 shoreline. This bathymetry was constructed from a typical 1995 beach profile, surveyed to the south of the inlet influence, which was duplicated along the shoreline region. This procedure provided an idealized profile base bathymetry within the eroding adjacent shoreline area that could be compared with the ebb shoal as it grew into this area. Values calculated from this method were slightly less than the volumes from the ebb-shoal edge (13-m-depth contour) and the difference

map methods (Table 1). The average rate of shoal growth was 147,800 m^3/year over the 62 years with this method.

Discussion of Methods - Receding and advancing inlet-adjacent shorelines will require modifying the area of calculation for all three methods. In the Ebb-Shoal Edge Method, a depth to shoal base was determined from profiles constructed through the ebb-shoal cross section (in this case, the 13-m-depth contour). Volume was calculated beneath the bathymetry and this base. Three area polygons were needed to account for the smaller area before the shoreline retreated and the shoal welded onto the island. The Difference Method subtracted one bathymetric surface from the next and used the area within the polygon that was above the 0-m contour indicating where the shoal had grown over the two time periods. Eroding areas would result in negative change. The Residual Method requires creating a no-inlet bathymetry, which in this case was satisfied by a pre-inlet bathymetry. The eroding shoreline, however, required a modification to account for the area where the inlet would eventually migrate.

These three methods for estimating ebb-shoal volume resulted in a calculated mean value of 10.32×10^6 m^3 and a standard deviation of less than 10 percent. In this test, the cumulative difference map method gave the largest values (10.8×10^6 m^3, 0-m contour), followed next by 10.3×10^6 m^3 (ebb-shoal edge method, above 13-m-depth contour), and the smallest 9.87×10^6 m^3 (residual method, above 0-m contour). This particular inlet was a good test case because of the known pre-inlet conditions. Inlets that have existed over recorded history or have had large adjacent shoreline changes will require care in identifying a no-inlet condition. Inlets that have migrated great distances in their historic evolution will require placing adequate boundary conditions to cover the entire area of ebb-shoal migration. The outcome of all three methods will depend on the quality, area of coverage, and frequency of historic data. Using more than one method and assigning possible sources of error (see Hicks and Hume 1997) will confirm the validity of results.

SUMMARY: The application of GIS technology to measure and analyze inlet shoal development quantifies shoal morphodynamics and evaluates large-scale and long-term inlet evolutionary processes. Figure 5 provides an example of the historic seaward and southward growth pattern of the ebb shoal at Ocean City Inlet. The reduction of historical data of different scales and datums to a comparable format provides a valuable resource that can be used in the following:

- Sediment budget calculations (past, present, and projected).
- Identifying evolutionary trends of the ebb shoal (growth, stability, or erosion).
- Documenting shoaling patterns and estimating trends in future dredging requirements.
- Predicting fate of sediment placed on the ebb shoal.
- Predicting impact of ebb-shoal mining.
- Identifying and mitigating effects of the inlet on adjacent shores.

ADDITIONAL INFORMATION:

For additional information on techniques to measure and analyze tidal inlet-shoal evolution, contact Dr. Donald K. Stauble, Coastal Evaluation and Design Branch, Coastal Sediments and Engineering Division, Coastal and Hydraulics Laboratory, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, at (601) 634-2056 or e-mail *d.stauble@cerc.wes.army.mil*, or the manager of the Coastal Inlets Research Program, Mr. E. Clark McNair, at (601) 634-2070.

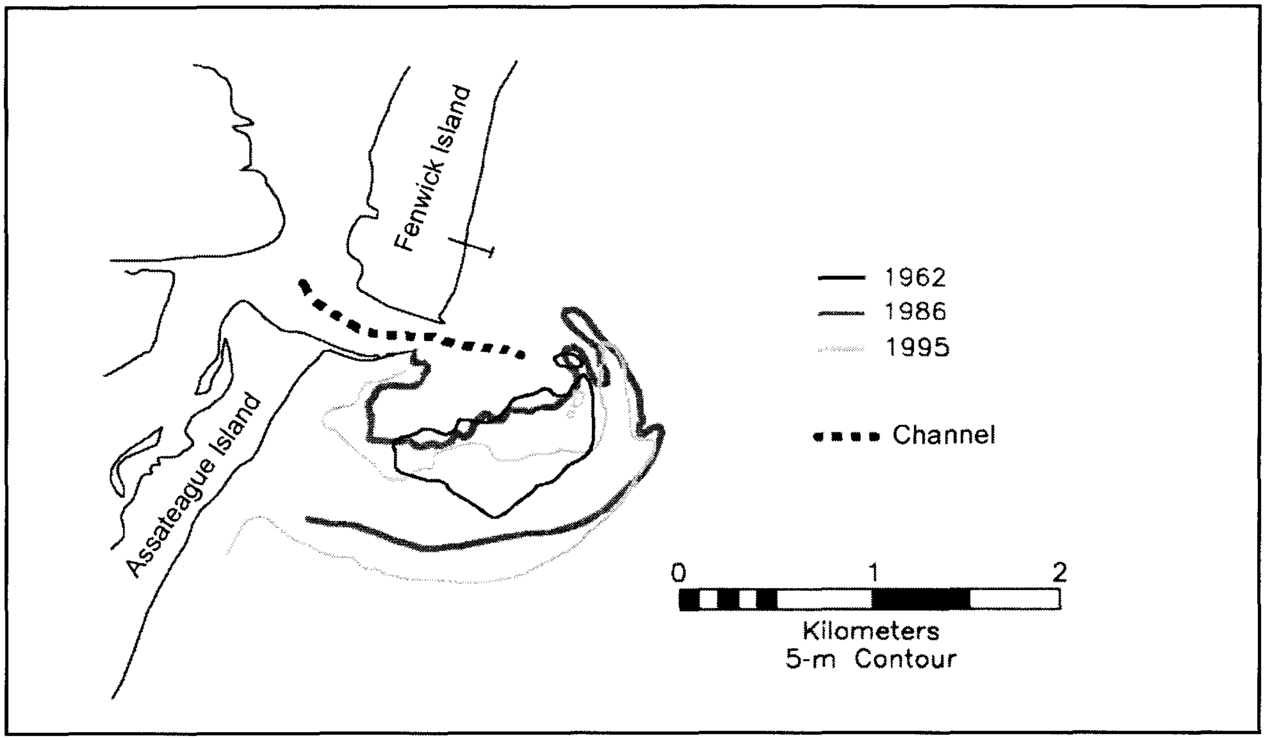

Figure 5. Historic seaward and southward growth of ebb shoal, Ocean City Inlet, Maryland

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